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Urban greenspace is associated with reduced psychological stress among adolescents: A Geographic Ecological Momentary Assessment (GEMA) analysis of activity space

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ABSTRACT

This study investigates the momentary association between urban greenspace, captured using Normalized Difference Vegetation Index (NDVI) derived from Landsat imagery, and psychological stress, captured using Geographic Ecological Momentary Assessment (GEMA), in the activity spaces of a sample of primarily African American adolescents residing in Richmond, Virginia. We employ generalized estimating equations (GEE) to estimate the effect of exposure to urban greenspace on stress and test for moderation by sex, emotional dysregulation, season, neighborhood disadvantage, and whether the observation occurs at home or elsewhere. Results indicate that urban greenspace is associated with lower stress when subjects are away from home, which we speculate is due to the properties of stress reduction and attention restoration associated with exposure to natural areas, and to the primacy of other family dynamics mechanisms of stress within the home. Subjects may also seek out urban greenspaces at times of lower stress or explicitly for purposes of stress reduction. The greenspace-stress association away from home did not differ by sex, emotional dysregulation, neighborhood disadvantage, or season, the latter of which suggests that the observed greenspace-stress relationship is associated with being in a natural environment rather than strictly exposure to abundant green vegetation. Given the association of urban greenspace with lower stress found here and in other studies, future research should address the mediated pathways between greenspace, stress, and stress-related negative health outcomes for different population subgroups as a means toward understanding and addressing health disparities.

1. Introduction

Psychological stress is a risk factor not only for mental disorders such as depression and anxiety, but also for a wide range of other ailments, including stroke, heart attack, and substance use disorders (Iwata, Ota, & Duman, 2013; O'Donnell et al., 2016; Rosengren et al., 2004; Sinha, 2008). Recent research indicates that exposure to vegetation and natural areas can mitigate psychological stress by providing opportunities for physical activity and social interaction, as well as by engendering cognitive and physiological responses associated with psychological stress reduction and attention restoration following stressful experiences (Bratman, Hamilton, & Daily, 2012 Hartig, Mitchell, de Vries, & Frumkin, 2014). Such effects may be particularly pronounced for those living in urban areas, where exposure to urban vegetated or natural areas, referred to as 'urban greenspace,' may be limited. Indeed, research indicates that city residents have a higher level of psychological stress as compared to those living in rural areas (Dhingra, Strine, Holt, Berry, & Mokdad, 2009; Lambert, Nelson, Jovanovic, & Cerdá, 2015; Verheij, Maas, & Groenewegen, 2008). This is of particular concern given both the increasing concentration of the world's population in cities (Turner, Nakamura, & Dinetti, 2004) and inequities in exposure and access to urban greenspace (Wolch, Byrne, & Newell, 2014). Understanding the relationship between greenspace and psychological stress among urban residents is thus of utmost concern for the development of interrelated policies on urban health, environmental justice, and greenspace infrastructure (Maller, Townsend, Pryor, Brown, & St. Leger, 2006; Sullivan & Chang, 2011; WHO, 2012).

Most observational studies of urban greenspace and psychological stress or other indicators of mental health, however, have been limited to measures of greenspace exposure based on the residential neighborhood, or where measures of greenspace exposure and stress are asynchronous or are derived from recall-based surveys (e.g. Feda, Seelbinder, Baek, & Raja, 2015; Maas, Verheij, Groenewegen, Vries, & Spreeuwenberg, 2006; Markevych et al., 2014). Notably, the focus on

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the residential neighborhood may not adequately capture the actual exposure to an environmental condition, such as greenspace, and its effect on health, which can occur not only at the home location but also throughout an individual's activity space, i.e. the routine places visited throughout daily life (Browning & Soller, 2014; Kwan, 2012; Mennis & Mason, 2011). Further, recall based methods of recording the effect of contextual conditions on mood or psychological state, such as stress, are prone to error due to the lapse of time between environmental exposure and reporting (Shiffman, Stone, & Hufford, 2008).

In the present study, we aim to address these study design limitations in an investigation of the association between urban greenspace and psychological stress that utilizes in-situ and synchronous activity space-based measurements of greenspace exposure and stress. Unlike the majority of research on greenspace and mental health, which focuses on adults (Beyer et al., 2014; Roe et al., 2013; White, Alcock, Wheeler, & Depledge, 2013), we focus here on a relatively understudied population: urban, African American adolescents. Adolescents in the U.S. report similar rates of stress as adults, which can act as a catalyst for negative health outcomes over the lifespan (APA, 2014). Mechanisms of stress for adolescents may differ from adults, however, as adolescence marks a critical developmental period, and carries a unique set of physical, sociological, and psychological stressors. As compared to adolescents generally, urban, African American adolescents may be particularly prone to additional contextual social and environmental stressors, as many African American urban neighborhoods exhibit concentrated economic disadvantage and disorder, with attendant high levels of crime, substance use, and physical decay (Brenner, Zimmerman, Bauermeister, & Caldwell, 2013; Latkin & Curry, 2003; Mennis et al., 2016). Investigating the role of urban greenspace as a potential stress reducer among African American youth can contribute to a better understanding of the complex contextual mechanisms that influence stress among urban adolescents exposed to stressful environmental stimuli.

We use Geographic Ecological Momentary Assessment (GEMA), an approach integrating conventional EMA with Global Positioning Systems (GPS) and Geographic Information Systems (GIS), to capture and link momentary data on exposure to greenspace and psychological stress in the activity spaces of a sample of urban youth residing in Richmond, Virginia. Our primary research question is: Is exposure to urban greenspace associated with lower stress among a sample of urban, primarily African American, adolescents? Additionally, we inquire whether this association differs according to characteristics of the individual adolescent and environmental context of the observation. We employ generalized estimating equations (GEE) to estimate the effect of exposure to urban greenspace on stress, while controlling for demographic characteristics. We employ tests of moderation to investigate whether this association differs according to characteristics of the individual and the environmental contexts within which the association is observed.

2. Literature review

2.1. How urban greenspace affects stress

The idea of greenspace, or natural landscapes, as a place for respite and stress release for those living in cities has long been held colloquially, even going back to the writings of ancient Romans (Glacken, 1967) and the influential 19th century American urban planner Frederick Law Olmsted (1865). It is only recently, however, that scientists have turned their attention to investigating why, and how, greenspace influences psychological stress, particularly for city dwellers. Several theories have been proposed. Greenspace can act as a buffer against heavily trafficked roads or excessive noise (Nilsson & Berglund, 2006), increase feelings of privacy in residential neighborhoods, and reduce perceptions of crowding in densely populated areas (Day, 2000), issues which have been cited as reasons for observed high levels of stress among those living in urban areas (Hartig & Kahn, 2016). Greenspace can also enable opportunities for recreation and physical activity in natural areas (Home, Hunziker, & Bauer, 2012) and encourage positive social interaction among city residents (de Vries et al., 2013; Fan, Das, & Chen, 2011; Kuo, Sullivan, Coley, & Brunson, 1998; Maas, van Dillen, Verheij, & Groenewegen, 2009; Sullivan, Frumkin, Jackson, & Chang, 2014), which can, in turn, promote lower stress (Sugiyama, Leslie, Giles-Corti, & Owen, 2008), though this may be dependent on how well the urban greenspace is maintained and residents' perceptions of safety (Kazmierczak, 2013).

Other theories have been proposed that link greenspace more directly to psychological stress reduction (Bratman et al., 2012). Stress reduction theory posits that because humans evolved in natural settings, they are genetically predisposed to respond favorably to greenspace, particularly to those natural landscape configurations which were favorable to survival (Ulrich et al., 1991), such as those that were likely to afford drinking water and food, as well as the ability to forestall potential dangers, in pre-modern times. Thus, exposure to certain natural landscapes invokes an unconscious physiological response of lower stress. Another theory concerns attention restoration (Kaplan, 1995; Kaplan & Kaplan, 1989), where cognitive effort for certain tasks requires directed attention, which can result in attentional (or mental) fatigue. Such fatigue may be particularly acute in urban built-up areas, as the urban landscape can contain greater degrees of movement (e.g. cars, people) and visual and auditory stimuli as compared to natural environments, which can overload cognitive processing systems used for attentional focus. Immersion in natural environments allows the cognitive functioning for direct attention to rest, and is thus thought to enhance attention restoration, attenuate mental fatigue, and consequently relieve psychological stress (Sullivan, 2015).

2.2. Empirical evidence for greenspace and stress reduction

The past 20 years has seen increasing empirical evidence for the influence of exposure to vegetation and natural areas on psychological stress, including both observational and experimental study designs. In observational studies, the qualities of greenspace typically considered are the presence of vegetated land cover (i.e. trees, grasses, or shrubs) and, conversely, the absence of built-up land cover (i.e. roads, buildings, and other developed land uses). Urban greenspaces are often considered 'natural' areas in the literature, though, of course, any area within a city is likely to be strongly influenced in character by human development. Urban greenspaces are often demarcated as parks, gardens, or open spaces, though vacant lots or other unmaintained urban spaces may also contain extensive vegetation. Greenspace might also be considered to be embedded within the urban fabric via residential lawns, street trees, and grassy medians. Many observational studies of greenspace and stress or other psychological states use remotely sensed imagery to distinguish vegetated land from built-up areas (Roe et al., 2013; van den Berg, Maas, Verheij, & Groenewegen, 2010; White et al., 2013) or to derive vegetation indices as an indicator of greenspace, most commonly Normalized Difference Vegetation Index (NDVI). The NDVI is an index of vegetation 'greenness' and is best regarded as a measure of leaf abundancy in healthy, green vegetation (Tucker, 1979). The NDVI exploits the property of photosynthetically active vegetation to absorb most radiation in the visible region of the spectrum (VIS) and strongly reflect radiation in the near-infrared region (NIR), and is typically calculated as: NIR -VIS / NIR + VIS. Values of NDVI range from -1 to 1, with high values indicating a high density of healthy green leaves, negative values representing water features or snow, and values close to 0 representing barren land, rocks, or sand.

Several large-scale observational studies of stress or mental health have focused on greenspace exposure at the residential location. In a study of over 10,000 individuals in England, White et al. (2013) found that lower stress was associated with living in proximity to greenspace. Reduced physiological indictors of stress were also observed among disadvantaged individuals in urban Scotland living in close proximity to greenspace, as compared to those individuals who lived farther away (Roe et al., 2013; Thompson, Roe, Aspinall, & Mitchell, 2012). Research based in The Netherlands has shown that psychological stress and attendant rates of depression and anxiety are lower in areas with greater exposure to greenspace (van den Berg et al., 2010). A Danish study of more than 11,000 subjects found higher stress among those living more than one kilometer from a greenspace (Stigsdotter et al., 2010). Exposure to greenspace was also found to be associated with lower levels of psychological stress, as well as indicators of anxiety and depression, among a state-wide representative sample of residents of Wisconsin (Beyer et al., 2014).

Among experimental studies, Ulrich et al. (1991) found that subjects who viewed videos of natural, vegetated settings following induced stress showed significantly reduced physiological indicators of stress as compared to those who viewed urban settings, a finding which was recently reproduced in similar studies by Jiang, Li, Larsen, and Sullivan (2015). Bratman, Hamilton et al. (2015) found that subjects who took a brief walk in a vegetated natural area reduced both mental rumination and neural activity in an area of the brain associated with mental illness, as compared to subjects who took a walk in a busy, built-up urban area. Walks through vegetated park-like settings, as compared to walks through urban areas, have also been shown to improve both memory span and mood among individuals diagnosed with depression (Berman et al., 2012).

To the best of our knowledge, there has been little research on urban greenspace and stress focusing specifically on youth. In a cross-sectional study of 68 urban adolescents in Buffalo, NY, Feda et al. (2015), found that exposure to parks can act as a buffer against perceived stress, while a study of ten year old children residing in German cities found a relationship between greenspace exposure and lower blood pressure (Markevych et al., 2014). A study of youth in southern California found that short and long term exposure to greenspace at the residential location were associated with reduced aggressive behavior, which may be related to stress (Younan et al., 2016). It may also be the case that greenspace affects certain population subgroups differently, for instance, between males and females (Jiang, Chang, & Sullivan, 2014; Richardson & Mitchell, 2010). It has also been suggested that greenspace exposure may have particular health effects for youth with certain mental health conditions. Experimental research suggests that urban youth with attention deficit/hyperactivity disorder (ADHD) maintain better concentration after exposure to park settings (Taylor & Kuo, 2009), and that outdoor activities in natural areas can mitigate symptoms of ADHD among youth (Kuo & Taylor, 2004).

This body of research certainly supports the idea that urban greenspace is associated with reduced stress among adolescents. However, observational studies have primarily been limited to residential-based measures of greenspace exposure in which data on stress and greenspace exposure are captured asynchronously. In the present research, we aim to advance understanding of the greenspace-stress relationship through the use of GEMA, which allows us to observe the greenspace-stress relationship not only at home but throughout the activity space. Such an approach also allows us to investigate whether the greenspace-stress relationship differs between home and not-home settings, as well among different subgroups of adolescents, using self-reported stress and greenspace exposure data captured simultaneously in real time and in the adolescents' natural environments.

3. Data and methods

3.1. Subject recruitment

The present study uses data from the Social-Spatial Adolescent Study, a longitudinal study focusing on the contextual mechanisms of adolescent substance use. Study participants were recruited between 2012 and 2014, primarily from an adolescent medicine outpatient clinic at a large academic medical institution in Richmond, Virginia providing comprehensive primary and adolescent-specific specialty care services to over 3000 patients annually. Criteria for inclusion in the study were age (13–14 years old), patient status (a registered clinic patient), and residency (Richmond area resident). Eligible adolescents presenting to the adolescent clinic for routine or acute care were approached and invited to participate in the study while in the clinic's waiting room or pending arrival of the physician into the patient's exam room. Of the approximately 400 adolescents approached for recruitment to the study, 248 enrolled. Written informed consent was obtained from all parents and adolescents and the study was approved by the institutional review boards of both Virginia Commonwealth University and the Richmond City Health Department. Participants received nominal incentives for their time and effort. For more information on study data collection and methods, the reader is referred to Mason et al. (2015).

3.2. Geographic Ecological Momentary Assessment

For readers unfamiliar with Ecological Momentary Assessment (EMA), it is a data collection technique that involves repeated sampling of a subject's behaviors, moods, and experiences in real time, and in a subject's natural environment (Shiffman et al., 2008), often delivered via brief surveys over a mobile phone. EMA has been widely used in ecological studies of health behaviors and has more recently been extended to geographic EMA (GEMA) by using GPS to capture location at the time of EMA response (Epstein et al., 2014; Mennis, Mason, Ambrus, Way, & Henry, 2017). These 'EMA locations' serve to represent an individual's activity space, the routine places through which an individual moves during the course of their daily life for purposes of work, leisure, and so on, and can be linked to geographic data using GIS software in order to investigate the influence of exposure to environmental characteristics on health (Kirchner & Shiffman, 2016). In the present study, GEMA was used to capture momentary data on psychological stress and exposure to greenspace using the EMA locations of the sample of urban adolescents. All study participants were given a mobile phone with embedded GPS, and a brief EMA survey was administered 3–6 times per day over a four-day period every other month over the two year period during which the subject was enrolled in the study. Each EMA survey was delivered via a text message that included an embedded URL link to a web-based survey.

3.3. Measures

The outcome variable, self-reported psychological stress, was assessed through the EMA survey question "How stressed are you now?" with responses given on a 1 ("Not at all stressed out") to 9 ("Very stressed out") scale. Because the response was highly skewed, with 67% percent of EMA responses = 1, the stress variable was recoded as a three category ordinal variable, with values of 0 (low, original value = 1), 1 (medium, original values 2–4), and 2 (high, original values 5–9), where higher values indicate higher levels of reported stress.

Following other studies (Beyer et al., 2014; Markevych et al., 2014), greenspace was represented here using NDVI data derived from an Enhanced Thematic Mapper Plus (ETM+) image dated September 12, 2013, carried aboard NASA's Landsat 8 satellite and downloaded from public sources (http://earthexplorer.usgs.gov/). Related studies of greenspace and health have measured greenspace exposure by calculating the mean NDVI value within a certain buffer distance surrounding a subject's location (Markevych et al., 2014; Younan et al., 2016). In the present study, we use this approach based on a 100 m buffer distance, as this distance has been found to be efficacious in a greenspace-health study employing multiple buffer distances (Dadvand et al., 2014), and has also been found to match closely with a ground observer's estimation of greenspace exposure (Rhew, Vander Stoep, Kearney, Smith, & Dunbar, 2011). For each subject, the mean NDVI value of all the image pixels within 100 m of each EMA location was calculated to indicate exposure to greenspace.

Several demographic variables were used as controls, including age, race and sex. Age is coded in years and corresponds to the age of the subject at the time the EMA survey was completed. Sex was collected at baseline (coded as 1 = female and 0 = male). Because the sample is primarily African American (89%), race was coded as 1 = African American, 0 = not African American. To control for preexisting mental health conditions that can influence stress, we also included an index of emotional dysregulation, a feature of many mood disorders which affects emotional and behavioral responses to contextual stimuli, captured at enrollment. The dysregulation index is measured using a set 15 self-report items and is measured on a continuous scale (Mezzich, Tarter, Giancola, & Kirisci, 2001), and was recoded as a dichotomous variable with the cutoff at the median, coded as 0 (original values ≤ 13) and 1 (original values > 13). We also sought to control for neighborhood disadvantage at the location of the EMA response, as neighborhood disadvantage often co-occurs with stressful urban conditions such as crime and disorder (Brenner et al., 2013). We use an index of neighborhood disadvantage derived from Ross and Mirowsky (2001), where higher values indicate higher levels of disadvantage, composed of the following U.S. Census Bureau variables at the block group level: the percentage of households with income below the poverty level, the percentage of female-headed households with children, the percentage of adults with bachelor's degree or higher, and the percentage of owner-occupied housing units.

We also test whether the effect of greenspace on stress differs between boys and girls, as previous research suggests (Jiang et al., 2014), and differs according to emotional dysregulation, as we hypothesize that the effect may be stronger for those with pre-existing mental health conditions, as previous research suggests benefits of greenspace exposure for adolescents with ADHD (Taylor & Kuo, 2009). We also investigate whether the effect of greenspace on stress differs according to three characteristics of the environmental context of the EMA observation: the level of neighborhood disadvantage at the observation, the season in which the observation occurs, and whether the observation occurs at home or elsewhere. The effect of greenspace may differ according to neighborhood disadvantage because urban greenspaces in poorer neighborhoods sometimes serves as the locus of crime or substance use and thus may be perceived as dangerous (Wang, Brown, & Liu, 2015), resulting in higher, not lower, stress.

Regarding the season of the EMA observation, most trees and shrubs in Richmond are deciduous and lose their leaves in the winter. If, indeed, healthy green vegetation affects stress, it stands to reason that season would affect the efficacy of the modeled greenspace effect on stress. To test this, we encoded the season of when each EMA survey response occurred, dichotomized into 'Leaf On' (April–October, coded as 1) and 'Leaf Off' (November–March, coded as 0) periods. We also accounted for whether the subject was at home at the time of EMA response, as the home often carries substantial emotional associations due to family relationships, and thus the greenspace-stress association may differ between the home and other locations where the EMA response occurs. One of the EMA survey questions asks where the respondent is at the time of the EMA response, which we use to encode whether the respondent is at home (1) or not home (0).

3.4. Analytical plan

We employ ordinal logistic GEE using an exchangeable correlation structure at the individual level to estimate the effect of greenspace on stress while controlling for age (at EMA), sex, race, emotional dysregulation, setting, season, and neighborhood disadvantage. GEE are well-suited for analyzing repeated measures data collected through GEMA methods (Mennis et al., 2016), as is the case in the present study. We then test whether the association between greenspace and stress is moderated by setting (home versus non-home), season (leaf on versus leaf off), sex (girls versus boys), emotional dysregulation (high versus low), and neighborhood disadvantage. Each test of moderation is implemented in a separate model by entering an additional interaction term composed of the greenspace variable multiplied by the moderating variable.

Table 1
Characteristics of the Subjects (N = 179).

Variable	Count	%
Age at Enrollment		
13	97	54%
14	82	46%
Sex		
Female	103	58%
Male	76	42%
Race		
African American	159	89%
Not African American	20	11%
Emotional Dysregulation		
Low	91	51%
High	88	49%

4. Results

The EMA yielded 24,601 responses over the two year period of the study. Of these, 10,193 contained geographic coordinates, a location data capture rate consistent with other GEMA studies in urban areas where buildings and other urban features can attenuate the GPS satellite signal (Watkins et al., 2014). We restricted our sample to EMA observations which contained valid geographic coordinates located within the Richmond, Virginia study region and for subjects for whom there were no missing data for any of the variables of interest. This yielded 9346 EMA responses for 179 subjects, with a mean of 52 EMA survey responses per subject.

Table 1 shows demographic characteristics of the sample. Out of the 179 subjects, 89% are African American, 58% are girls, and 54% were age 13 at enrollment. Table 2 reports descriptive statistics from the EMA data. In approximately two thirds of the EMA surveys (67%) the adolescents reported low stress. EMA surveys were collected for subjects between the ages of 13–16, with 72% collected at ages 14–15. Approximately 72% of EMA responses occurred at home, which is not

Table 2
Descriptive statistics of the EMA survey data (N = 9346). The categorical coding for each variable is reported in parentheses.

Variable (Coding)	Count	%
Stress		
Low (0)	6277	67%
Medium (1)	1475	16%
High (2)	1594	17%
Age at EMA		
13	1546	16%
14	3335	36%
15	3357	36%
16	1098	12%
Setting		
Not Home (0)	2586	28%
Home (1)	6760	72%
Season		
Leaf Off (0)	3645	39%
Leaf On (1)	5701	61%
Variable	Min, Max	Mean (SD)
Greenspace	−0.22, 0.75	0.48 (0.14)
Disadvantage	−4.59, 3.60	0.13 (1.8)

Fig. 1. Examples of areas with low greenspace exposure (top images) and high greenspace exposure (bottom images). To maintain subject privacy, the images do not show actual sites of EMA locations, but sites with greenspace character similar to the actual EMA locations. Image source: Google Earth.

surprising given the age of the subjects and that EMA surveys were delivered during after-school times and on weekends, and 61% were captured during the Leaf On period.

Greenspace varied from −0.22 through 0.75, with a mean of 0.48. To illustrate the distinction between low and high greenspace exposure locations, Fig. 1 shows examples of four areas with relatively low (top images) versus high (bottom images) greenspace exposure. These images depict sites in the study area which are analogous to those of the sampled EMA locations but do not reveal the sites of any actual EMA locations. EMA survey responses collected at low greenspace exposure locations typically occurred in commercial areas with extensive pavement, such as shopping developments or commercial corridors along major thoroughfares (NDVI ~0.2), as depicted in the top, left image, or at residential, multi-family apartment complexes composed of larger buildings interspersed with lawn and sparse tree cover (NDVI ~0.4), as depicted in the top, right image. EMA surveys collected in areas of high greenspace exposure were typically found in residential areas composed of single family homes with extensive lawn and tree cover (NDVI ~0.6), as depicted in the bottom, left image, or in park-like settings with extensive, high density tree cover (NDVI ~0.7), as shown in the bottom, right image.

The GEE regression results are presented in Table 3. Model 1 shows results for the direct effects of greenspace on stress after controlling for age, sex, race, emotional dysregulation, neighborhood disadvantage, setting, and season. Greenspace is not significantly associated with stress in this model. However, high emotional dysregulation and responding to the EMA at home (as opposed to elsewhere) are both significantly associated with higher stress. Models 2, 3, 4, 5, and 6 report the results of the tests of moderation by setting, season, sex, emotional dysregulation, and neighborhood disadvantage, respectively. Of these five, only setting is significant as a moderator ($OR = 1.98$, $p < 0.05$), where greenspace is associated with lower stress at EMA responses that occur when the subject is away from home.

This moderation by home versus away from home setting is illustrated in Fig. 2, which plots the relationship between greenspace and the cumulative estimated probability of high (as compared to low)

Table 3
Results of the generalized estimating equations (GEE) models of stress, with tests of moderation (odds ratios reported with 95% confidence intervals in parentheses, reference categories given for dichotomous variables [see text for explanation]); $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.005$.

Variable	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Age at EMA	0.96	0.96	0.96	0.95	0.96	0.96
	(0.81–1.12)	(0.81–1.12)	(0.81–1.12)	(0.81–1.12)	(0.81–1.12)	(0.81–1.13)
Sex	2.69	1.08	1.10	0.81	1.11	1.11
(Ref = Male)	(0.00–1.77)	(0.66–1.77)	(0.69–1.76)	(0.43–1.52)	(0.69–1.78)	(0.69–1.80)
Race	0.88	0.85	0.88	0.87	0.87	0.84
(Ref = Not AA)	(0.43–1.79)	(0.39–1.83)	(0.44–1.77)	(0.43–1.75)	(0.43–1.77)	(0.42–1.71)
Dysregulation	2.51***	2.61***	2.57***	2.64***	2.32**	2.48***
(Ref = Low)	(1.58–3.99)	(1.62–4.23)	(1.62–4.09)	(1.64–4.29)	(1.26–4.27)	(1.56–3.95)
Season	1.08	1.07	1.16	2.08	1.08	1.08
(Ref = Leaf off)	(0.91–1.28)	(0.90–1.27)	(0.73–1.86)	(0.91–1.28)	(0.91–1.28)	(0.91–1.28)
Setting	1.23***	0.89	1.23***	1.22***	1.23***	1.23***
(Ref = Not home)	(2.56–1.38)	(0.66–1.22)	(1.10–1.39)	(1.09–1.38)	(1.10–1.39)	(1.10–1.39)
Disadvantage	1.00	1.01	1.00	1.00	1.00	0.94
	(0.97–1.03)	(0.98–1.04)	(0.97–1.03)	(0.97–1.03)	(0.97–1.03)	(0.83–1.07)
Greenspace	0.90	0.66	1.09	0.64	0.90	1.04
	(0.66–1.48)	(0.40–1.09)	(0.55–2.19)	(0.36–1.15)	(0.45–1.80)	(0.68–1.60)
Greenspace X		1.98*				
Setting		(1.05–3.75)				
Greenspace X			0.85			
Season			(0.35–2.04)			
Greenspace X				2.03		
Sex				(0.94–4.39)		
Greenspace X					1.17	
Dysregulat.					(0.51–2.69)	
Greenspace X						1.15
Disadvantage						(0.87–1.53)

stress for EMA responses which occurred at home (dotted line), versus those which occurred away from home (solid line). Note that the intercept is higher for EMA surveys collected at home as compared to those collected away from home – i.e. subjects have higher stress at home. However, of particular importance here is that for the EMA responses that occurred at home, the slope is close to zero, indicating that at home there is no significant relationship between greenspace exposure and stress. For EMA responses that occurred away from home, the slope is substantially steeper and negative, indicating that stress tends to be lower in areas of high greenspace exposure.

Because we found that home versus not home setting moderates the effect of greenspace exposure on stress, we conducted a supplementary analysis, where we tested five additional three-way moderation models, to investigate whether the moderating effect of home versus away-from-home setting differs by season, sex, emotional dysregulation, or neighborhood disadvantage. These models were parameterized by

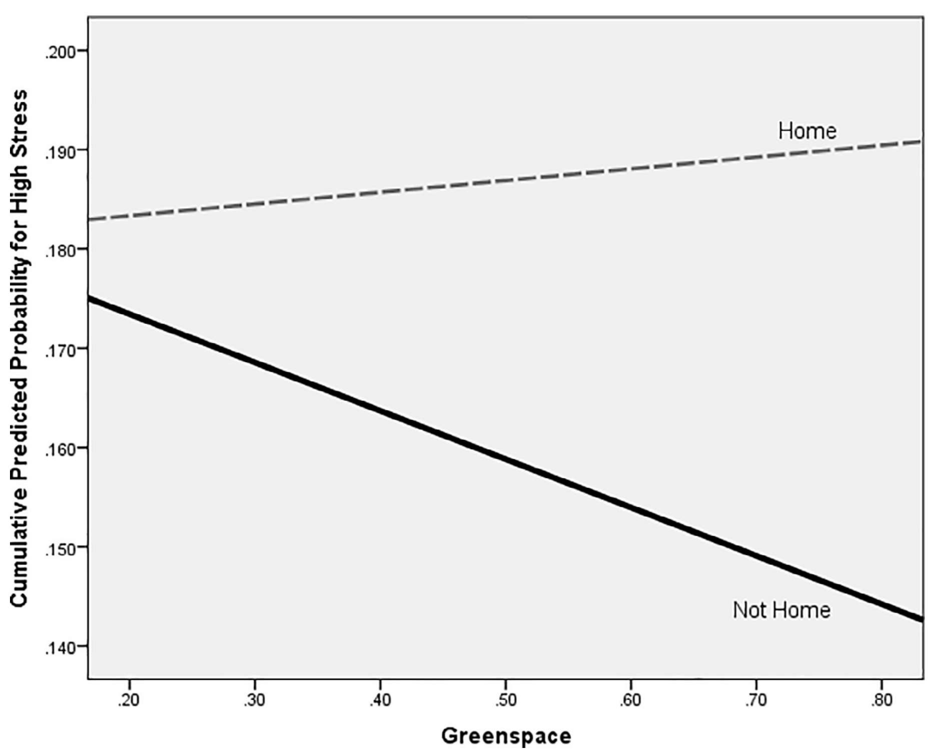

Fig. 2. The association between greenspace and the cumulative predicted probability of high stress (Table 3, Model 2) for EMA observations taken at home (dashed line) and not-home (solid line) settings.

Table 4
Results of the three-way moderation generalized estimating equations (GEE) models of stress (odds ratios reported with 95% confidence intervals in parentheses); All models are adjusted for control variables listed in Table 3; $^{*}p < 0.05$.

Variable	Model 7	Model 8	Model 9	Model 10
Greenspace X Setting	1.94 (0.60–6.27)	1.16 (0.42–3.23)	1.30 (0.39–4.31)	2.06* (1.09–3.93)
Greenspace X Season	0.85 (0.24–3.09)			
Greenspace X Sex		1.09 (0.38–3.08)		
Greenspace X Dysregulat.			0.76 (0.26–2.21)	
Greenspace X Disadvantage				1.03 (0.72–1.47)
Season X Setting	0.93 (0.49–1.75)			
Sex X Setting		0.84 (0.46–1.54)		
Dysregulat. X Setting			0.73 (0.37–1.44)	
Disadvantage X Setting				0.96 (0.76–1.22)
Greenspace X Setting X Season	1.46 (0.25–4.33)			
Greenspace X Setting X Sex		2.43 (0.67–8.78)		
Greenspace X Setting X Dysregulat.			2.11 (0.53–8.51)	
Greenspace X Setting X Disadvant.				1.12 (0.69–1.82)

entering additional two-way and three-way interaction terms in separate regression equations for each three-way interaction. However, these latter moderation tests did not yield any significant three-way interaction terms (Table 4).

5. Discussion

The present study extends previous research on greenspace and psychological stress in several ways. To the best of our knowledge, this is the first study to investigate greenspace exposure and stress using momentary activity space data gathered through GEMA. This approach, which leverages advances in mobile and geospatial technologies with innovative survey techniques, affords data collection on stress and greenspace exposure in real time and in subjects' natural environments, substantially extending previous observational study designs which focus on greenspace exposure at the residential location and which use measurements of stress acquired asynchronously to greenspace exposure. In addition, while most previous studies of greenspace and stress have focused on adult populations, the present study extends this prior research to a relatively understudied group – urban, primarily African American, adolescents.

Our research provides evidence that exposure to greenspace in the activity spaces of urban adolescents is associated with lower psychological stress. These findings are consistent with previous observational studies of adults and youth alike that have found that exposure to vegetation as measured at the residential neighborhood is associated with reduced stress (Beyer et al., 2014; van den Berg et al., 2010; White et al., 2013), and align with experimental studies that have shown that exposure to natural areas is associated with lower blood pressure and other physiological markers of lower stress (Bratman, Daily, Levy, & Gross, 2015; Brown, Barton, & Gladwell, 2013; Jiang et al., 2015). We speculate that the association of greenspace with lower stress found in our study is due to the properties of stress reduction, attention restoration, and the amelioration of mental fatigue associated with exposure to vegetation and natural areas (Kaplan, 1995; Ulrich et al., 1991) among urban residents, though we cannot distinguish between these mechanisms here. We note that many of the subjects in the sample live in relatively disadvantaged communities. Thus, these adolescents may be particularly vulnerable to stressful environmental conditions associated with economic deprivation and neighborhood disorder. It may be that greenspace exposure has a particularly attenuating effect on the influence of neighborhood disadvantage on stress (Mitchell & Popham, 2008) through the partial alleviation of stressful environmental stimuli associated with impoverished neighborhoods.

Interestingly, we did not find that the association between greenspace exposure and stress differs between boys and girls or between adolescents with high and low emotional dysregulation (although, not surprisingly, we did find that high emotional dysregulation itself is strongly associated with higher stress). While prior research indicates that the effects of greenspace on health may differ by gender (Jiang et al., 2014; Richardson & Mitchell, 2010) or may be particularly effective for those with certain mental disorders, such as ADHD (Taylor & Kuo, 2009), our results suggest that the association of greenspace exposure with stress persists for both boys and girls, as well as for those with high and low measures of emotional dysregulation. We also found that the effect of greenspace exposure on stress did not fluctuate according to the level of neighborhood disadvantage or season – whether there were leaves on the trees or not. If, indeed, it is exposure to green vegetation that lowers stress one would expect the relationship to occur only during, or at least be stronger during, periods in which the trees had abundant green leaves. The fact that no moderation by season was detected suggests that the association of greenspace with stress has more to do with being in a natural environment generally, rather than the seasonal abundancy or vitality of green vegetation specifically.

Notably, we found that the association of greenspace exposure with lower stress occurs only in activity space locations away from home. One reasonable explanation is that family oriented mechanisms of stress at home not accounted for in the present study, such as the relationship of the subject with his or her parents, interact with exterior contextual conditions to influence mood and behavioral outcomes (Mason et al., 2016). It may also be the case that subjects are more likely to be outside, and thus more prone to the effects of environmental stimuli like greenspace exposure, when they indicate that they are not at home in the EMA survey. However, many of the activity space locations outside the home indicated by the sample are also indoors, such as the homes of friends or relatives, shopping malls, and so on. And it is also likely that some adolescents who indicate in the EMA survey response that they are at home, may in fact, not be indoors but rather in their yard or outside in their neighborhood nearby their home. Notably, we did not find a substantial difference in greenspace exposure between home EMA locations (mean = 0.49, SD = 0.13) and those away-from-home (mean NDVI = 0.46, SD = 0.16).

Psychological stress as measured at the moment of EMA survey response is also likely influenced by the activity and social context in which subjects are engaged at that moment. It may be that certain activities, such as doing homework, are more stressful and certain social contexts, such as hanging out with friends, are less stressful. Such activities and social interactions may be more or less likely to occur at home versus other locations outside the home. The role of place, activity, and social context, and their interaction with exposure to greenspace, with regards to psychological stress represents a ripe area for future research.

It is useful to question whether individuals with greater greenspace exposure away from home tend to have lower stress generally, or whether an individual's time-varying stress level is reduced during the moments that they are exposed to more greenspace away from home. The use of GEE in repeated sampling designs, as in the present research, emphasizes between-person effects. We note that the mean within-person variance in greenspace exposure at away-from-home EMA observations is 0.022, and it differs significantly across subjects ($F = 3.77$, $p < 0.005$). This research thus supports the former interpretation – greater greenspace exposure away from home is associated with lower stress across individuals – though it certainly does not preclude the latter interpretation. Future research using multilevel growth modeling may elucidate the distinction concerning these between-person and within-person effects of greenspace exposure on changes in stress levels over the course of adolescent development (Curran & Bauer, 2011).

Because our data capture the exposure to greenspace and stress simultaneously, and our analysis treats the data as a cross-sectional repeated sample over multiple subjects, we are unable in the present analysis to disentangle mechanisms of influence versus selection. Though we presume theoretically that exposure to greenspace causes a reduction in stress, other mechanisms are possible. For instance, someone who actively intends to lower stress may be more likely to visit a natural environment outside the home for purposes of mental restoration (Bratman et al., 2012; Hartig & Staats, 2006). This is certainly consistent with attention restoration theory regarding the use of natural environments in urban areas to 'decompress' from the high stimuli associated with urban environments, and the role of visiting a favorite place and environmental choice in emotional self-regulation (Korpela, Hartig, Kaiser, & Fuhrer, 2001; Mason et al., 2010). In this case, while greenspace may contribute to lower stress, it is also a result of the agency of the individual in seeking stress reduction, and thus not wholly a contextual effect of greenspace exposure itself. Further, it is possible that adolescents seek out greenspace at moments when they are feeling less stressed; In this case, the observed association of greenspace with lower stress would not necessarily be due to the influence of greenspace on stress reduction but a product of the place selection associated with a priori low stress moods.

6. Conclusion

We acknowledge several limitations of this study. First, the sample is limited to 179 urban, primarily African American, adolescents recruited from a single city in Virginia. How our findings generalize to other populations of different race/ethnicity or in different urban, suburban, or rural regions is unknown. Second, the stress variable used here is a relatively simple measure of self-reported stress on a continuous 1–9 scale. More sophisticated multi-item indices of stress, physiological indicators of stress, or narrative interviews may be more effective at capturing the stress outcome, although the use of GEMA, in which subjects are required to submit repeated short surveys on a series of items, necessitates the use of a relatively simple measure which can be captured quickly. Third, while GEMA affords an innovative approach to capturing in situ measurements of greenspace exposure and stress, issues of survey compliance and accuracy remain a concern (Mennis et al., 2017). Finally, there may be other mechanisms of stress for which we have not accounted in the model, including social interactions, prior traumatic life experiences, and mental health conditions not captured by the emotional dysregulation index, that may explain in part or in whole the observed association between greenspace and stress.

We also acknowledge that parameterization of the greenspace and outcome variables can influence the statistical results. To address this, we ran models using a categorical greenspace measure and using a linear model with a continuous stress variable outcome. We also ran models controlling for within-block group autocorrelation and models without the neighborhood disadvantage variable included. In all cases, results were substantially the same as those presented here. We also acknowledge that the use of a 100 m buffer to calculate the mean NDVI around a point location may not perfectly capture greenspace exposure, and that our analytical results may be sensitive to changes in the buffer distance. While the use of such a buffer distance does not, by itself, indicate the particular causal mechanism by which greenspace might influence stress, it does suggest that the effect may be due to the amount of greenspace in one's immediate surroundings or visual field, as opposed to the larger neighborhood.

Despite these limitations, the present study contributes to the growing literature concerning the psychological and health benefits of urban greenspace using a novel GEMA methodological approach. These findings have important implications for policy, where urban development policies that promote greenspace infrastructure, whether park development, street tree planting and maintenance, or natural area preservation, are recognized as having an impact not only on urban livability and aesthetics but also on health. As Bratman, Daily et al. (2015) note, urban greenspace can be considered to provide 'psychological ecosystems services' in the same way we consider vital ecosystem services that provide water, air, and food. The recognition of greenspace as both a recreation amenity and health amenity has led to recent research investigating urban greenspace access as an environmental justice issue (Wolch et al., 2014), as urban greenspace is not distributed equitably with regards to race and socioeconomic status, with minorities and the poor often living in areas with less greenspace (Astell-Burt, Feng, Mavoa, Badland, & Giles-Corti, 2014). Given the association of greenspace exposure with stress found here and in other studies, future research should address the mediated pathways between greenspace, psychological stress, and stress-related negative health outcomes for different population subgroups as a means toward understanding and addressing health disparities.

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